

## THE INFLUENCE OF TMP FIBRE FLEXIBILITY ON FLOCCULATION AND FORMATION

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Fibre flexibility is often anticipated to play a role in fibre flocculation phenomena. In this study, 3 thermomechanical pulps (TMPs) were sampled along a post-refining line. The only fibre morphological property that varied was fibre flexibility. These TMP samples were then tested for fibre flocculation and sheet formation tendency. The measurements clearly showed that fibre flocculation decreased and sheet formation uniformity increased with increasing fibre flexibility. The beneficial effect of fibre flexibility was larger at high consistency. These results support the elastic energy storage theory within flocs, which states that the more rigid the fibre, the stronger the flocs. Papermakers may take advantage of the beneficial effect of fibre flexibility on sheet formation through a careful tuning of post-refining.

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### INTRODUCTION

The papermaker is interested in the mass distribution of fibres within the suspension, since the quality of the distribution governs the quality of the end-product. The non-uniform distribution of mass density is referred to as flocculation in the suspension and formation nonuniformity in the sheet. This corresponds to the visual impression of homogeneity when viewing a sheet of paper in transmitted light. Good control of fibre flocculation in the suspension before forming can help improve the visual quality of the sheet produced by the papermachine.

Fibre flocculation is one of the key factors that affects paper formation, together with drainage conditions. The pioneering work of Mason (1950, 1954) led to the concept of a critical concentration, which corresponds to the concentration at which one fibre is statistically independent in the suspension. Kerekes et al. (1985) defined a crowding factor  $N$  as the number of fibres in a volume swept out by the length of one fibre as it rotates about its center. The crowding factor  $N$ , which can be viewed as a dimensionless concentration accounting for fibre morphology, has proved to be a useful tool to describe fibre flocculation (Kerekes and Schell 1992; Huber et al. 2003). Shearing conditions throughout the circuits and headbox also greatly modify fibre flocculation.

When reviewing the parameters affecting flocculation, Mason (1954) pointed out the influence of fibre curl, flexibility, and bending under stress from the hydrodynamic flow field. Little research has ever been done about the influence of fibre flexibility on flocculation, although it is anticipated to be of great importance. According to Meyer and Wahren (1964), fibres entangle in the flow, bend, and remain networked in flocs. The

flocs are kept stable by frictional forces transmitted by fibres that are locked into bent configurations. In order to verify this hypothesis, Soszynski and Kerekes (1988) flocculated nylon fibres under shearing, then heated the suspension; they observed redispersion of the flocs above the glass transition temperature of nylon, corresponding to relaxation of bending forces. Therefore, cohesive energy of the flocs is likely to depend on fibre flexibility. Jokinen and Ebeling (1985) stated that with increasing consistency, the flocculation tendency of stiff pulps increased more than that of flexible pulps, although some other fibre morphology parameters varied as well. Computer simulations at the fibre level by Schmid and Klingenberg (2000a,b) indeed showed that floc coherency is linked to elastic energy storage in fibres, provided there is sufficient friction between fibres. The sliding between two fibres (which helps floc disruption) depends on the coefficient of friction, which may be linked to macro-fibrillation for a given sample. This is an important parameter to follow, as it been shown that fibre surface fibrillation has a large impact on sheet formation (Stoere et al. 2001). Using the flexure theory of elastic beams, Farnood et al. (1994) proposed that floc strength is inversely proportional to fibre flexibility, among other parameters. Kaji et al. (1991) measured the flocculation of softwood kraft pulp before and after beating in a PFI mill; flocculation was reduced (= improved), presumably due to an increase of fibre flexibility, as fibre length remained constant.

Depending on the pulping processes, large variations of fibre flexibility can be observed; decreasing the yield from levels typical of mechanical pulps to those of chemical pulps decreases fibre stiffness by a factor of 10 or more (Kerekes and Tam Doo 1985).

To summarise, flexibility is listed as a morphological parameter that is likely to influence mechanical fibre flocculation, in addition to the crowding factor. Technically, it is not easy to vary fibre flexibility without affecting other morphological parameters. To our knowledge, the effect of fibre flexibility on flocculation has never been measured directly. In the literature, only models are proposed, which state that the more rigid the fibre, the higher the bending force at contact point, and the stronger the floc. Following this theory, making the fibre more flexible, should reduce fibre flocculation and improve sheet formation. The objective of this study is to assess the impact of fibre flexibility on flocculation and corresponding sheet formation.

## **EXPERIMENTAL**

Three pulp samples were obtained from a continental European mill, along a TMP line, feeding 100% of a ULWC machine. The TMP\_0 was sampled at the outlet of the washpress (at 35% consistency, following a 0.6% peroxide bleaching stage), while the TMP\_1 and TMP\_2 were sampled before and after post-refining, respectively (at a concentration of 5 %, with specific energy applied of 175 kWh/t BD). The only process change between TMP\_0 and TMP\_1 was a dilution with PM white waters, and some residence time (pipes/chests). The TMP\_1 and TMP\_2 pulp samples were then pressed to 28% dry content on the CTP pilot wire press (under conditions so that fines losses were

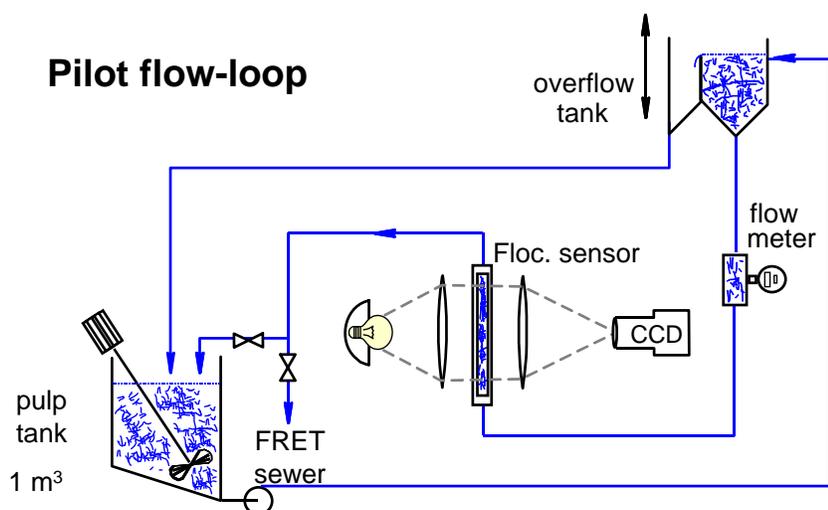
negligible), before doing any measurements. The freeness values of TMP\_0, TMP\_1, and TMP\_2 were 73, 79, and 83 °SR, respectively.

Morphology of the TMP fibres was measured with a Morfi analyser (Eymin-Petot-Tourtollet 2000). The macro-fibrillation index was measured on the Morfi analyser as well, through image analysis. This parameter represents the ratio of total fibrils length to total fibre+fibrils length (down to a scale of 3 µm), and it characterises external macro-fibrillation. The wet fibre flexibility was measured with a CyberFlex analyser (for comparison, a typical bleached softwood kraft pulp sample was tested as well, Cellulose du Rhône Tarascon, refined to 24 °SR, ref “SW”). As described by Das et al. (1999), the CyberFlex automates the Mohlin-Steadman method, which simulates the mechanical bending and chemical bonding that fibres undergo during sheet formation. Wet fibres are bent over a metal wire anchored to a glass slide. While fibres will bond to the glass on either side of the wire, their unbonded spans will extend some distance from the wire. The length of the unbonded area is used along with other fibre physical properties to compute fibre flexibility.

The flocculation analyser was implemented in a pilot scale flow loop, where the pulp suspension was continuously circulated. Fibres were thoroughly mixed in a 1 m<sup>3</sup> tank, where the temperature was regulated at 35±2°C (Fig. 1). The stock was pumped to an overflow tank, from which the static head controlled the pulp flow rate. The pulp suspension flowed through a transparent flat channel (thickness  $b = 3.5$  mm), where it was observed in transmitted light. Image analysis technique (Huber et al. 2006) made it possible to obtain the floc size distribution (the diameter of the disk of equivalent surface area was used as a measure of floc size). The histogram of total floc surface  $S_i$  in each size class  $i$  of equivalent floc diameter  $D_i$  could then be constructed. Floccs were categorized in 20 fixed size bins between 0.7 and 9.1 mm. The Flocculation Index  $FI$  was calculated as the raw moment of second order of the floc size distribution. It had dimension of mm<sup>2</sup>. It can be viewed as the surface of an average floc. The evolution of  $FI$  follows that of the RMS index, in the absence of light diffusing mineral filler. The defined flocculation index was thus correlated with the visual impression, without filler. Each flocculation measurement was a compilation of 100 to 600 images (60x60 mm<sup>2</sup>), so that the number of detected floccs was roughly constant. The precision on the flocculation index was about 2%.

For each of the three TMP samples, the concentration  $C$  was varied over five levels from about 2 to 10 g/L. For each concentration level the flow speed  $V$  was varied over six levels from about 0.7 to 2.1 m/s (corresponding to shear rates  $\tau = 2V/b$  ranging from 400 to 1200 s<sup>-1</sup>).

This range of shear rate can be observed on a papermachine running from 550 to 1650 m/min (with a slice aperture of 23 mm). As a comparison, Tam Doo et al. (1984) estimated the shear rate at the slice at about 400 s<sup>-1</sup> for a papermachine running at 610 m/min, using detailed numerical flow analysis.



**Fig. 1.** Implementation of flocculation sensor in the flow loop

In order to measure corresponding sheet formation, handsheets were prepared. A 2g sample taken at the outlet of the flocculation sensor was immediately poured into a retention handsheet former “FRET” (Techpap, Gières, France), which makes it possible to form handsheets at headbox consistency and shear level. The pulp sample was stirred at 500 rpm for 4 s, was allowed to rest for 2 s, and was finally drained for 2 s with a vacuum of 400 mbar through a bronze single forming fabric (Martel Catala, Tricot 25/cm, newspaper grade). This gave superficial drainage velocities between 3 to 15 cm/s, which is within the range of commercial forming applications (Wildfong and Genco 2003). Handsheets were dried on a Rapid Köthen apparatus. For each furnish, only three levels of concentration were tested (2, 4, 6 g/L), as the sheet formation was not acceptable at higher concentration. The homogeneity of formation was evaluated as the coefficient of variation CV of the grammage G. The handsheet was observed in transmitted light by a CCD camera. The intensity of the light source was regulated, so that the average observed luminance was constant (to minimise the influence of possible sheet grammage variations). Then  $CV(G)$  was calculated through standard image analysis, at the pixel level (i.e. 0.25 mm). Note that variations of scattering coefficient caused by refining might affect the determination of CV in optical formation measurements; however this will have no influence on the fibre flocculation measurements, as floc size is determined independently of opacity.

## RESULTS AND DISCUSSION

From fibre analysis (see Table 1), it can be seen that fibre length, width, coarseness, and macro-fibrillation did not change across the dilution step and post-refining operations. The only measured morphological change was a fibre flexibility increase (Fig. 2). The post-refining improved fibre flexibility without any fibre cutting or fibrillation effect (Fig. 3). The dilution step also slightly increased fibre flexibility, possibly due to a latency effect after a high consistency pressing and enhanced fibre

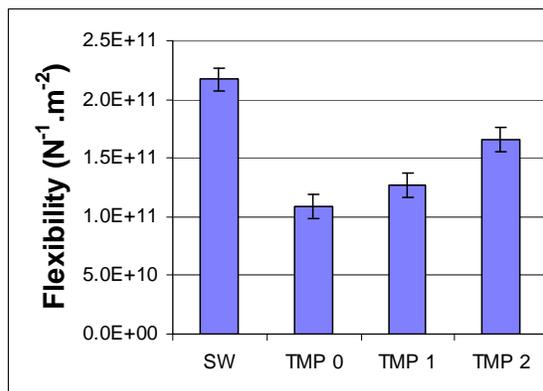
swelling after an alkaline bleaching treatment. The fact that the macro-fibrillation index did not change among the samples suggests that the coefficient of friction between fibres will remain constant, and it will not affect flocculation (Stoere et al. 2001).

As a comparison, the TMP\_2 fibre flexibility was about half that of typical SW kraft fibres. Chemical pulp fibres are much more flexible than high-yield pulp fibres. Usually, the lower the cooking yield, the higher the flexibility. The difference can be attributed to the larger lignin fraction that has been leached from the kraft fibre (Kerekes and Tam Doo 1985).

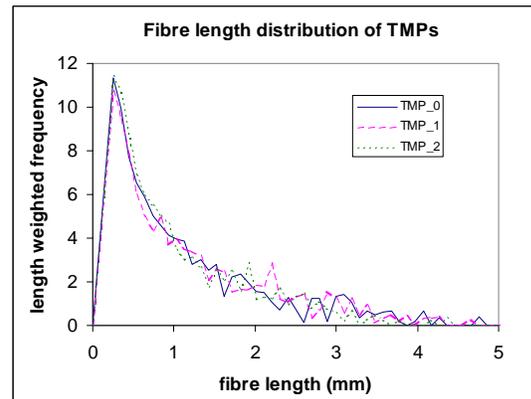
Using those three TMP samples, it was possible to study the effect of a fibre flexibility increase on flocculation, independently of other morphological changes.

**Table 1.** Fibre Morphology of TMP Samples, and the SW Reference

reference		SW	TMP 0	TMP 1	TMP 2
Length weighted length (mm)	( $\pm 0.05$ )	1.92	1.10	1.15	1.08
Width ( $\mu\text{m}$ )	( $\pm 0.4$ )	28.5	26.3	26.4	26.6
Coarseness (mg/m)	( $\pm 0.03$ )	0.14	0.15	0.15	0.16
Flexibility Cyberflex ( $\text{N}^{-1} \cdot \text{m}^{-2}$ )	( $\pm 0.1\text{E}+11$ )	2.2E+11	1.1E+11	1.3E+11	1.7E+11
Macrofibrillation index (%)	( $\pm 0.1$ )	0.5	2.3	2.2	2.3



**Fig. 2.** Fibre flexibility (Cyberflex) of the TMP fibres; a typical bleached softwood kraft pulp is shown for comparison.



**Fig. 3.** Evolution of fibre length distribution of TMP fibres upon post-refining

The general fibre flocculation behaviour of the three TMP samples as a function of concentration and shear rate was similar to what has been observed earlier with mixtures of SW and HW pulps (Huber et al. 2003). Flocculation increased more or less linearly with consistency, and a higher shear rate deflocculated the pulp (Fig. 4). The higher the consistency, the larger the effect of shear rate, while at low consistency (2 g/L), the shear rate had almost no effect on fibre flocculation.

To assess the effect of fibre flexibility on flocculation, measurements have to be compared at similar concentration and shear rate levels. Two-dimensional linear interpolation of the data was performed (Fig. 5), so that the effect of fibre flexibility could be studied at specified concentration and shear rate levels (Fig. 6).

When comparing the three TMP samples at the highest concentration (9.6 g/L) and the lowest shear rate ( $440 \text{ s}^{-1}$ ), it appears that the fibre flocculation of the TMP\_2 sample was significantly lower than that of TMP\_1, which was then significantly lower than that of TMP\_0 (Fig. 5). Then, for each interpolated shear rate level, the flocculation index was plotted as a function of fibre flexibility and concentration (Fig. 6). It appears clearly that in all conditions, the more flexible the fibre, the lower the flocculation index. This confirms the hypothesis that flocs made of flexible fibre are more easily disrupted in the shear flow, compared to flocs formed from more rigid fibres. The observed effect of fibre flexibility was larger at high consistency. This interaction between flexibility and concentration is in accordance with results by Jokinen and Ebeling (1985). The beneficial effect of post-refining on flocculation can be quantified as a flocculation index decrease of  $-1.4 \text{ mm}^2$  (at high shear rate  $\tau=1109 \text{ s}^{-1}$  and  $C=9.6 \text{ g/L}$ ). That positive effect is equivalent to a dilution from a 9.6 g/L concentration to 7.2 g/L. The corresponding visual impression is exemplified in Fig. 7.

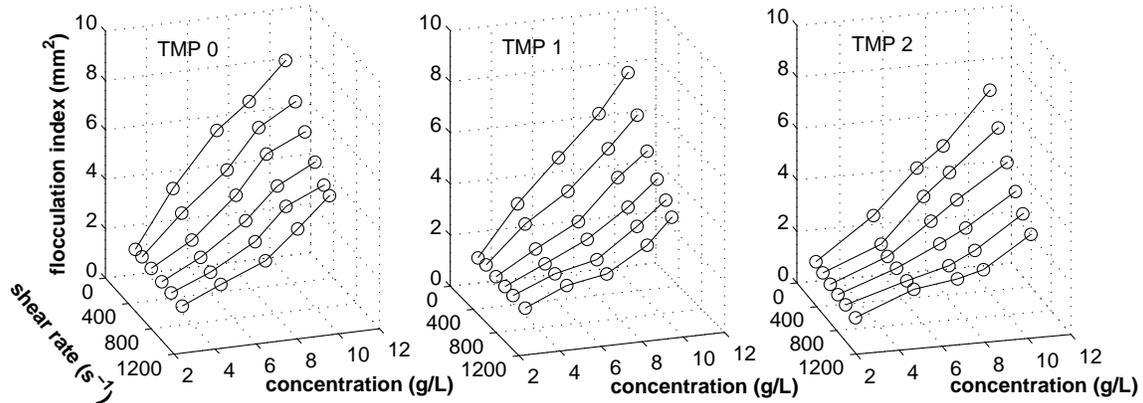


Fig. 4. Flocculation raw data for the 3 TMP samples: influence of consistency and shear rate

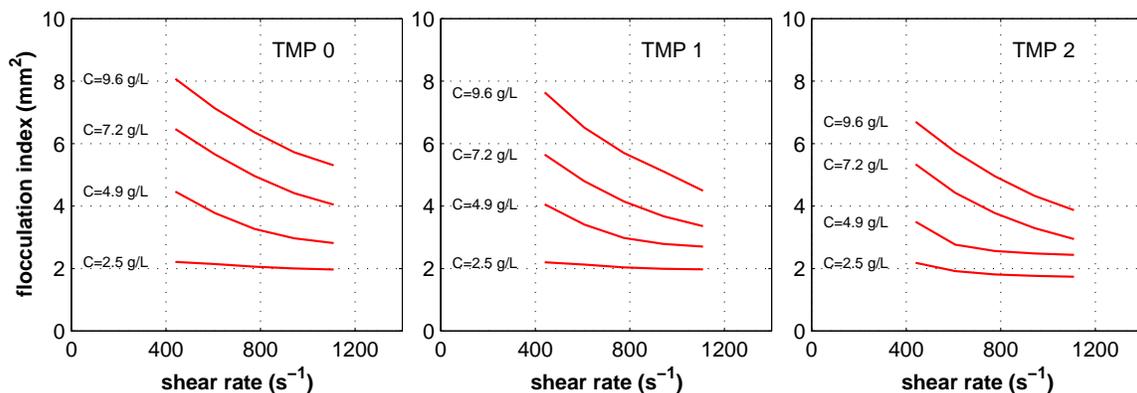
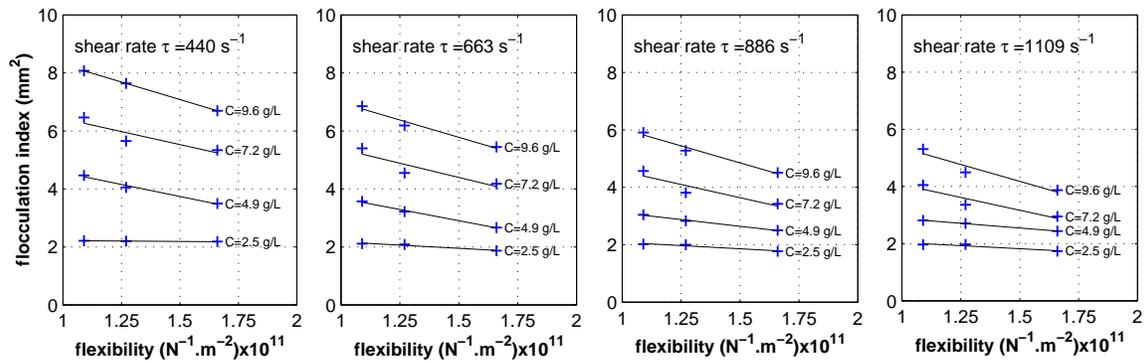
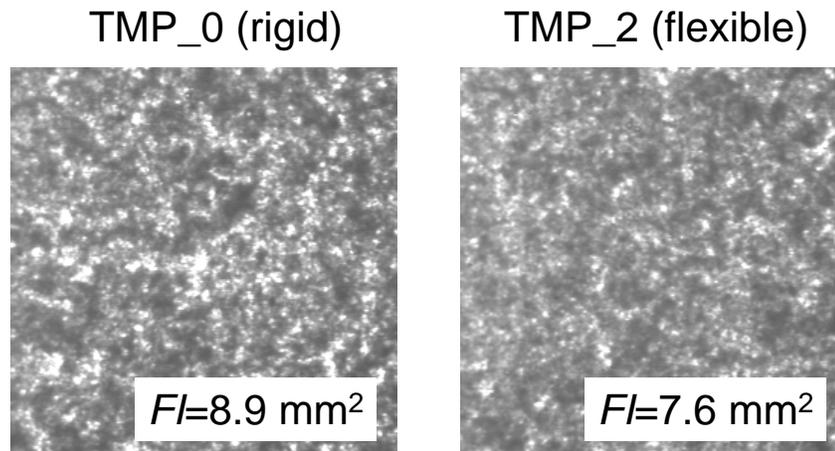


Fig. 5. Comparison of flocculation tendency for the 3 TMP samples: interpolation at fixed consistency and shear rate



**Fig. 6.** Influence of TMP fibres flexibility on flocculation, as a function of consistency, at given shear rates.

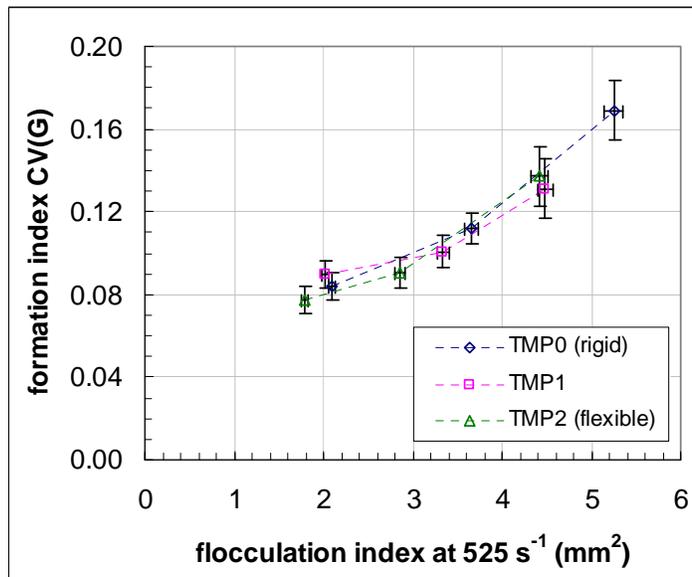


**Fig. 7.** Visual impression: Effect of flexibility on flocculation index ( $C = 9.8 \text{ g/L}$ ,  $\tau = 345 \text{ s}^{-1}$ )

Then handsheets were made under similar conditions. The flocculation index made it possible to compare furnishes independently of machine forming/drainage conditions; however such data is not directly related to paper properties. The handsheet formation index, on the other hand, takes into account both flocculation and drainage phenomena. Therefore it is dependent on the forming device (here the FRET), and it is difficult to transfer the results to a paper machine, because every paper machine has a different forming/drainage set-up.

The stirrer speed in the FRET bowl can be adjusted. However, in the absence of retention aids, the re-flocculation kinetics are so fast ( $1/10^{\text{th}}$  of a second, see Karema et al. 1999), that stirring speed can be expected to have no influence on sheet formation. It was decided to stir the sample at a constant low speed of 500 rpm before forming (for homogenisation purposes only), and to compare the formation results to the flocculation results at a low shear rate of  $525 \text{ s}^{-1}$  in all cases. The homogeneity of formation was evaluated as the coefficient of variation CV of the grammage G: the higher the CV(G), the worse the formation.

When looking at the general flocculation/formation relationship, it appears clearly that fibre flocculation had a strong influence on sheet formation (see Fig. 8), whatever the type of furnish. This is probably due to the fact that the three furnishes had similar drainage behaviour during the forming step. Under these given conditions, fibre flocculation was a very good indicator of sheet formation, and the measurement had a better precision.



**Fig. 8.** Sheet formation index vs. fibre flocculation at low shearing

From the handsheets, we tried to determine the influence of fibre flexibility on sheet formation uniformity. In order to compare formation measurements among the furnishes, formation indexes were interpolated at 2 consistency levels (3.35 g/L and 5.25 g/L, out of the 3 concentration levels available). As expected, formation improved when decreasing the forming consistency from 5.25 to 3.35 g/L. Sheet formation was also found to improve significantly with fibre flexibility, at the highest consistency level (Fig. 9). At the lowest consistency level, a similar decreasing trend was observed, but the effect of flexibility was within the 95% confidence interval. Similarly to the flocculation behaviour, the effect of fibre flexibility on sheet formation was coupled with consistency: the higher the consistency, the larger the beneficial effect of fibre flexibility on formation. The beneficial effect of fibre flexibility on sheet formation was comparable to a 2 g/L dilution in the case of the stiffest fibre sample.

These results imply that papermakers may take advantage of the beneficial effect of fibre flexibility on sheet formation through a careful tuning of post-refining. In the present study it was however not possible to trace back and identify the specific refining conditions that caused this fibre flexibility increase without affecting other morphological properties.

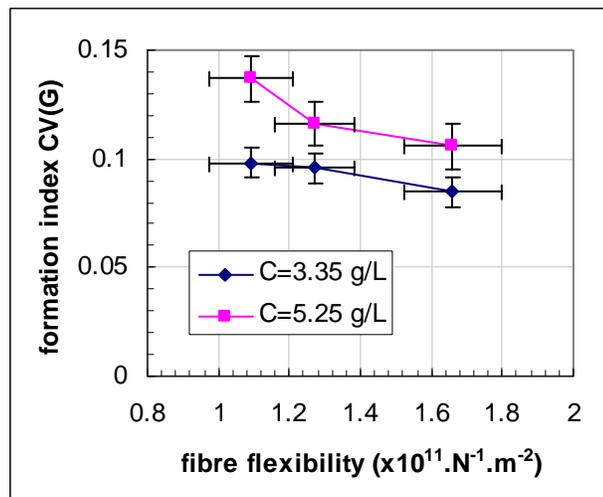


Fig. 9. Influence of fibre flexibility on sheet formation (at 2 interpolated forming concentrations)

## CONCLUSIONS

1. Enhancing fibre flexibility through post-refining was found to be beneficial for both minimization of fibre flocculation and to achieve the most uniform sheet formation, in the case of TMP fibres. The higher the consistency, the larger the relative influence of fibre flexibility. In this particular case, the beneficial effect of post-refining on flocculation was equivalent to a dilution from 9.6 to 7.2 g/L (at a high shear rate of  $1100 \text{ s}^{-1}$ ).
2. With all TMP samples, sheet formation was strongly correlated to fibre flocculation.

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